

The resonant magnetic mode: a common feature of high- T_C superconductors

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Abstract

Inelastic neutron scattering experiments in high- T_C cuprates have evidenced a new magnetic excitation present in the superconducting state. In particular, recent experiments on single layer $\text{Ti}_2\text{Ba}_2\text{CuO}_{6+\delta}$, performed near optimum doping ($T_C \sim 90$ K), provide evidence of a sharp magnetic resonant mode below T_C , similar to previous reports on the YBCO and BSCCO bilayer systems. This result supports models that ascribe a key role to magnetic excitations in the mechanism of superconductivity.

Key words: Superconductivity; $\text{YBa}_2\text{Cu}_3\text{O}_7$; Inelastic neutron scattering; Magnetic fluctuations

1. Introduction

Fifteen years after the discovery of high- T_C superconductivity, its mechanism is still the subject of vigorous debate. The experimentally established $d_{x^2-y^2}$ -wave symmetry of the superconducting (SC) order parameter favors an origin based on antiferromagnetic (AF) interactions [1]. However, a strong electron-phonon coupling has been inferred from anomalies of the electronic dispersion measured by photoemission spectroscopy experiments [2], among others. The resonant magnetic mode observed in the inelastic neutron scattering (INS) spectra in the SC state is one of the most persuasive experimental indications of the importance of magnetic interactions for superconductivity in the cuprates. Starting from the $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ (YBCO) system [3,4,5,6,7], numerous INS studies have established the existence of this magnetic excitation mode as a generic feature of the high- T_C superconductors. The presence of the mode has been demonstrated in another CuO_2 -bilayer cuprate $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (BSCCO) [8,9] as well as in a single-layer system,

$\text{Ti}_2\text{Ba}_2\text{CuO}_{6+\delta}$ [10]. We here review this feature for these different copper oxide systems where the maximum superconducting temperature reaches 90 K.

2. Resonance peak is generic to 90 K cuprates

Since its first discovery in near-optimally doped YBCO [3], the resonance peak has been established as a sharp excitation mode centered at the wave vector (π, π) that is characteristic of AF state in the insulating cuprates. One of its key features is its disappearance in the normal state: the peak intensity vanishes at T_C without substantial energy renormalization. Polarized neutron experiments [4,5] have unambiguously demonstrated its magnetic origin. For optimally doped YBCO and BSCCO, the peak is observed close to ~ 40 meV (table 1). One main difference between the two systems is the broadening of the peak in both energy and wave vector in BSCCO [8]. In particular, an energy width of ~ 13 meV is found in BSCCO whereas the peak is almost resolution-limited in YBCO. That difference might be related to the intrinsic inhomogeneity

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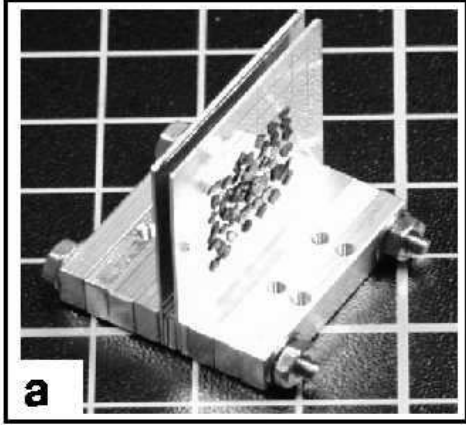


Fig. 1. Photograph of the array of co-oriented $\text{Tl}_2\text{Ba}_2\text{CuO}_{6+\delta}$ single crystals. The crystals are glued onto Al plates only two of which are shown for clarity. The entire multicrystal array is equivalent to a single crystal with a mosaicity of 1.5° on which regular transverse acoustic phonons can be measured (from [10]).

genities found in BSCCO by STM measurements where a substantial spatial distribution of the SC gap was reported [11]. It is also known that the magnetic resonance is extremely sensitive to defects: both magnetic (Ni) [12] or non-magnetic (Zn) [13] impurities produce a marked energy broadening of the resonance peak in YBCO, even in very dilute concentrations.

Most electronic properties of the high- T_c superconductors (including superconductivity) are assumed to be determined by the commonly shared CuO_2 layers. As a result, most theoretical models of high temperature superconductivity are based on a two-dimensional square lattice. As the resonant mode had only been observed in copper oxide systems which have in common two CuO_2 layers per unit cell, the relevance of this mode for all high- T_c superconductors was questioned, as it could be related to interlayer interactions that vary substantially among the copper oxides. In particular, the resonance peak has never been reported in the most widely studied single layer cuprate, $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$. However, the maximum T_c of this system is only about 38 K. Until recently, the investigation of another single layer cuprate whose maximum T_c can reach 90 K remained one of the major challenges in the field.

We therefore recently focused our effort on $\text{Tl}_2\text{Ba}_2\text{CuO}_{6+\delta}$, a material with unbuckled, widely spaced CuO_2 layers and a maximum T_c around 90 K. The crystal growth of the Tl-based copper oxide superconductors suffers from technical difficulties arising from the toxicity of Tl, and only single crystals with moderate volumes of about $\sim 0.5\text{-}3\text{ mm}^3$ can be obtained through a CuO-rich flux technique [14]. To

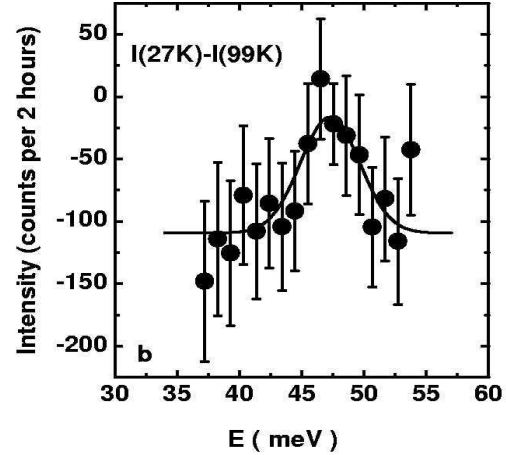


Fig. 2. Difference between constant- Q scans measured at $T = 99\text{ K}$ ($> T_c$) and $T = 27\text{ K}$ ($< T_c$) at the antiferromagnetic wavevector (from [10]).

perform INS, which requires large single crystals of minimum volume $\sim 0.1\text{ cm}^3$, an array of more than 300 co-aligned single crystals had to be assembled (see photo Fig.1) [10]. Using high-flux triple axis spectrometers at LLB-Saclay (France) and ILL-Grenoble (France), we were able to observe a resonance peak for this array [10]. Fig. 2 shows the difference of energy scans in the SC state and the normal state at the AF wave vector: it exhibits the characteristic signature of the resonant mode, albeit at an energy of 47 meV that is somewhat larger than the mode energy in the bilayer compounds (see table 1).

In many aspects, the resonant mode in $\text{Tl}_2\text{Ba}_2\text{CuO}_{6+\delta}$ shows strong similarities with that observed in YBCO₇. In both cases, the mode is limited by the resolution in energy and exhibits the same extension in q -space (see table 1). Further, the resonance peak spectral weight per CuO_2 layer, defined as $\int d\omega d^3Q \text{Im}\chi^{res}(\mathbf{Q}, \omega)$, equals $(0.02\mu_B^2/eV)$ for both of these systems. In BSCCO, where the resonance q -width along the diagonal (110) direction is about twice as large, the spectral weight is larger, but the energy integrated intensity at the AF wavevector, normalized to one CuO_2 layer, is almost identical for the three different cuprates (see table 1).

3. Resonance peak spectral weight

The resonant mode at (π, π) represents the major part of the experimentally observable magnetic spectrum for the optimally doped cuprates. Going into the underdoped state, as experimentally realized for different oxygen contents in YBCO [6,7], this mode shifts to lower energy as shown in Fig. 1. Further, INS studies of

	2-layers		1-layer
Cuprates	YBCO	BSCCO	Tl-2201
Resonance energy (meV)	41	43	47
$E_r/k_B T_c$	5.1	5.4	6
$\Delta_q (\text{\AA}^{-1})$	0.25	0.52	0.23
$\int d\omega \text{Im}\chi^{res}((\pi, \pi), \omega) (\mu_B^2/eV f.u.)$	1.6	1.9	0.7
$\int d\omega d^3\mathbf{Q} \text{Im}\chi^{res}(\mathbf{Q}, \omega) (\mu_B^2/eV f.u.)$	0.043	0.23	0.02

Table 1

Resonance peak energies, q -width (Full Width at Half Maximum) and spectral weights per formula unit at optimal doping for three different cuprates.

underdoped $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ reveal a complex lineshape incorporating the resonant mode at (π, π) . Across T_c , a drastic magnetic intensity redistribution occurs in both momentum space [15] and energy [6]. Incommensurate excitations at somewhat lower energies than the resonance peak energy at (π, π) are observed. They form a downward dispersion relation continuously connected to the commensurate resonance peak energy at (π, π) [15]. In the overdoped regime, as observed so far only in one BSCCO sample [9], the resonant mode also shifts down to lower energy (Fig. 3).

Besides the observation of the magnetic resonance peak below T_c by INS, anomalies in the quasiparticle spectra has been also reported by photoemission [16], optical conductivity [17], tunneling [18], and Raman scattering techniques. Their interpretation as an evidence of the coupling of quasiparticles to the neutron mode has stimulated spin fluctuation based pairing scenarios which are, however, still controversial [2]. It should be noted that, for all doping levels in YBCO, the resonance peak spectral weight is almost constant [6], $\int d\omega d^3\mathbf{Q} \text{Im}\chi^{res}(\mathbf{Q}, \omega) \simeq 0.05 \mu_B^2/f.u.$, and represents about 2 % of the spectral weight contained in the spin wave spectrum of undoped YBCO_6 . This seemingly rather small spectral weight is, however, highly concentrated at wave vectors that connect extended saddle points in the band structure. Depending on how the magnetic spectrum and the density of states of charged quasiparticles are modeled, the resonance peak cannot [19] or can [20] account for various anomalies detected in charge spectroscopies of the cuprates. In any case, the spectral weight is large enough to account for a sizable fraction of the superconducting condensation energy [19,20,21], and so the resonant mode must be considered as a key player in theories of high- T_c superconductivity.

4. Models

In any superconductors, INS experiments have the potential to perform a complete identification of the

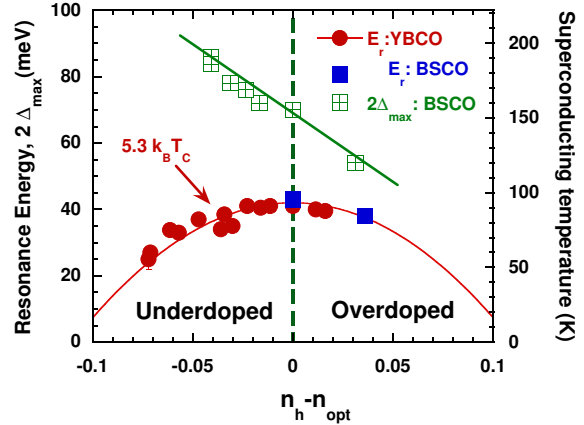


Fig. 3. Doping dependence of the resonance energy at (π, π) in YBCO and BSCCO from Refs. [3,6,7,8,9] as a function of various doping levels referenced to the optimal doping level, n_{opt} , corresponding to T_c^{max} . The doping level has been determined through the empirical relation $T_c/T_c^{max} = 1 - 82.6(n_h - n_{opt})^2$ [29]. n_{opt} is generally identified as a hole doping level of 16 % although this assumption is not necessary here. The red full curve shows the doping dependence of the superconducting temperature times 5.3. The figure also shows twice the maximum SC gap as measured in BSCCO by ARPES [30].

symmetry of superconducting order parameter. As emphasized by Joynt and Rice[22], the knowledge of wavevector and energy-dependent spin susceptibility in superconductors indeed reflects directly the vector structure of the SC gap function. In high- T_c superconductors, the observation magnetic excitations at (π, π) is, for instance, fully consistent with the d-wave symmetry of SC order parameter[23].

More precisely, the resonant mode can be theoretically modeled as a spin exciton collective bound state pulled below the threshold of particle-hole (p-h) excitation continuum in the d -wave SC state by magnetic interactions [24,25]. The consistency of this idea can be quantitatively tested for the BSCCO system where the SC gap and the Fermi surface have been measured by photoemission spectroscopy. A close inspection of the Fermi surface [28] shows that the quasi-particles which are connected by the (π, π) momentum (corresponding to the "hot spots") have the energy $E_k \simeq 0.9\Delta_{max}$ at the Fermi level. The p-h continuum threshold would then be $\omega_c \simeq 1.8\Delta_{max} \simeq 63$ meV (where the SC gap measured at optimal doping is $\Delta_{max} = 35$ meV [30]). The resonance peak is observed at optimal doping at an energy around 43 meV, clearly lower than ω_c . A ratio $E_r \simeq 1.2\Delta_{max}$ is found, indicating that the resonance peak occurs well below the p-h continuum in agreement with this theoretical approach. To confirm these ideas, one might eventually be able to detect the p-h spin-flip continuum threshold directly by INS. For YBCO, BSCCO and $\text{Tl}_2\text{Ba}_2\text{CuO}_{6+\delta}$, $2\Delta_{max}$ can also

be determined by the position of the B_{1g} mode in Raman scattering, which occurs around 70 meV for the three cuprates [31]. Furthermore, the observation of a higher resonance energy in $Tl_2Ba_2CuO_{6+\delta}$ (whereas the SC gap maximum is similar) can be explained by the non-negligible value of the interplane magnetic coupling in bilayer systems which could push the bound state to lower energy. Therefore, the spin exciton scenario is consistent for the different cuprates assuming a similar Fermi surface topology. As shown by Fig. 3, the resonance peak energy exhibits a dome-like shape as a function of doping following, an approximately linear relationship with T_c [9] on both sides of the optimal doping level.

Alternatively, other approaches [26,27] associate the resonance peak to a pre-existing soft mode reminiscent of nearby (commensurate or incommensurate) AF phase. While the collective mode decays into p-h excitations in the normal state, it becomes undamped below ω_c in the SC state, giving rise to neutron peak. In that framework, the apparent absence of the mode in the $La_{2-x}Sr_xCuO_4$ system, could imply that the condition $E_r < \omega_c$ may not be satisfied [26]. In addition, predictions of the influence of impurities on the line shape of the mode [27] agree well with measurements in YBCO [13].

In line with those approaches, the dispersive resonance peak has been re-examined within a stripe model [32], where the observed dispersion [15] corresponds to the trace of spin-waves emanating from incommensurate Bragg reflections shifted away from (π, π) . This approach agrees with the spin dynamics measured in stripe-ordered nickelates [33]. However, a detailed comparison of the temperature and momentum dependences of the magnetic spectrum in the cuprates and nickelates does not favor this model as a general scenario for the cuprates.

5. Conclusion

In conclusion, the magnetic resonance is a generic feature of high- T_c cuprates, at least for systems with a maximum T_C^{max} of around 90 K. The resonant mode occurs at an energy E_r always lower than twice the superconducting gap (Fig. 3) $E_r < 2\Delta_{max} \sim 70 \text{ meV} \sim 9k_B T_c$, which has been deduced either by photoemission measurements in BSCCO [30] or by the position of the B_{1g} mode in Raman scattering; the latter has been measured for all cuprates. This agrees with models which interpret the resonant mode as a magnetic collective mode of the $d_{x^2-y^2}$ -wave superconducting state below the electron-hole continuum.

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